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Surface micromachined scanning mirrors

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Abstract

Both aluminum cantilever and torsional scanning mirrors have been fabricated and their static and dynamic properties are studied experimentally and theoretically. The experiments showed resonance frequencies in the range of 163 kHz - 632 kHz for cantilever beams with Q values between 5 and 11. Torsional mirrors showed resonance frequencies in the range of 410 kHz - 667 kHz with Q values of 10 - 17. All measurements performed at atmospheric pressure. Both types of mechanical structures were deflected electrostatically at large angles ($\pm 5^\circ$) more than 10^{11} times without breaking and without any noticeable deterioration due to fatigue. A number of different light modulator arrays made up of adjacent devices was investigated and the measured performance parameters were in good agreement with calculations.

1. Introduction

Depending on the ability to produce inexpensive and highly reliable micromechanical scanning mirrors integrated with driving electronics, there are a number of potentially powerful applications. These includes, among others, projection displays and printing arrays.¹ In the area of high precision moveable head structures such as print heads the components are subject to an additional restriction of compactness since the heads must be moved rapidly across a surface. The devices described here has the advantage that they can be formed directly upon a integrated driving circuit. Their fabrication requires only two additional masking steps using a thick photoresist as a sacrificial layer. With a very high reliability and the IC-compatibility the prototypes of micromachined scanning mirrors presented here seems to be very attractive for fabrication of projection displays and printing arrays.

2. Fabrication of the cantilever and torsional mirrors

On a polished $\langle 100 \rangle$ silicon wafer a 3000 Å thermal SiO₂ is grown. A thick photoresist layer (AZ 1450 J) is then spun onto the wafer and patterned using normal photolithographic processes. It is important to assure a good step coverage of the aluminum layer that is evaporated next. A second photoresist layer is then spun on the aluminum layer and patterned

using standard photolithographic processes. The aluminum layer is wet etched in a phosphoric acid (52°C, 2:1 H_3PO_4 : H_2O). The thin torsional beams are defined by undercutting the mask. This etch is controlled to a beam dimension standard deviation of $\pm 0.1 \mu\text{m}$. The wafers are then cut into individual chips and placed in a barrel plasma stripper. The working conditions of the 20 % oxygen/ 80 % nitrogen plasma must be well controlled during this operation in order to avoid mechanical stress that will cause deformations of the mirrors. The mirrors are then glued to a TO5 house with a conducting paste and gold wire bonded. A SEM photo of a completed micromachined torsional mirror is shown in figure 1 and a stepped cantilever beam is shown in figure 2. The torsional device shown has a $20 \times 20 \mu\text{m}^2$ mirror placed between two $1.2 \times 2.1 \times 10 \mu\text{m}^3$ beams. The stepped cantilever beam in figure 2 consist of a $15 \mu\text{m}$ long beam with a $20 \times 20 \mu\text{m}^2$ mirror formed at the end.

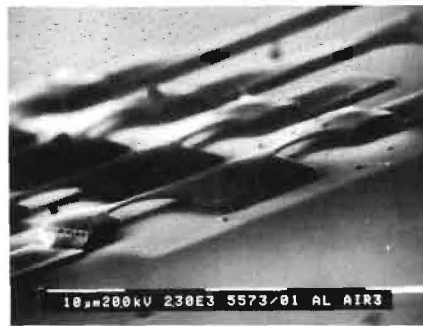


Fig 1. Torsional mirror device



Fig 2. Stepped cantilever beam.

3. Measured performance of the scanning mirrors

The characteristics of the scanning devices operating in air are determined experimentally by monitoring a laser beam deflected by the mirror device. To excite the devices a DC voltage with a superimposed AC sine voltage is applied between the aluminum structures and the substrate electrode. The measured performance of both cantilever beams and torsional beams will be presented in the two following sections.

3.1 Cantilever beams

In fig 3 the frequency responses of the stepped cantilver beam shown in fig 2 are obtained for two DC bias levels with the same AC sine voltage. For zero DC level only one resonance peak appear. Increasing the DC bias level results in the appearance of a peak at twice the frequency of the first peak. This second peak correspond to the first natural vibrating mode of a half frame.² Increasing the DC level further this second peak becomes dominant exhibiting a maximum scan angle of 16.6° for a DC level of 40 V. It were found that beyond a DC bias threshold of 48 V the cantilever beam were deflected totally. Approaching this threshold level the resonance frequency of the resonant beam is reduced with 10% as observed by Nathanson.³

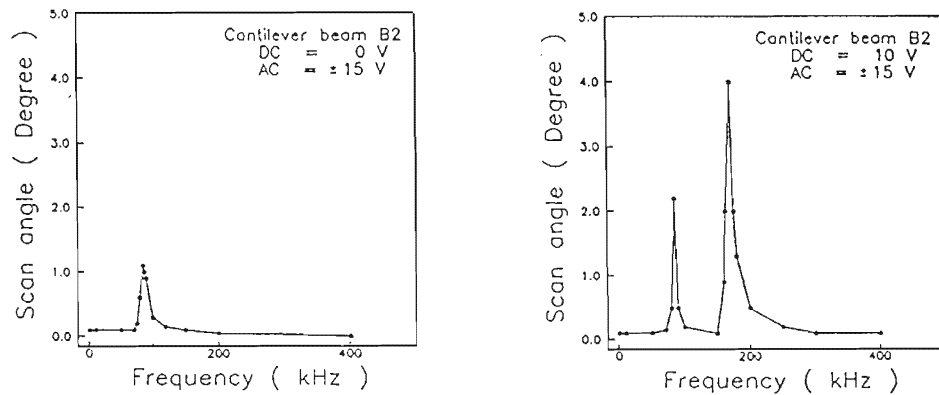


Fig 3. Frequency responses of the cantilever beam for a) $V_{DC} = 0V$, and b) $V_{DC} = 10 V$.

Only a slight shift in the resonance frequency is observed when the DC voltage is kept below a DC bias value of 35 V. The first resonance peak that can be observed in the frequency response of the scanning mirror devices is believed to be due to a "parametric resonance" of the electrostatic actuated device as can be found by evaluating the force expression given by Nathanson.³

3.2 Torsional beams

In fig 4 the frequency responses of a torsional scanning mirror are obtained for two DC bias levels with the same AC sine voltage. For zero DC level only small peaks at the "parametric position" and at the first resonant mode position is observed. Increasing the DC bias level results in the appearance of the first resonant mode of the scanning device. Increasing the DC level further the scan angle at resonance is increased to 12.4°. The threshold level of this device was found at 80 V.

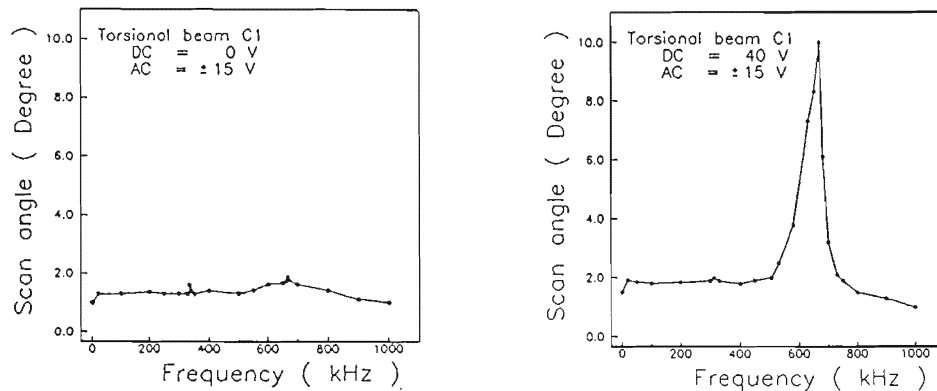


Fig 4. Frequency response of the torsional beam for a) $V_{DC} = 0V$, and b) $V_{DC} = 40 V$.

A considerable increase in the scanning angle is observed when the DC voltage level is increased. This is taking place without any reduction in the bandwidth. Only at DC voltages approaching the threshold level a shift in the resonance peak of up to 40 % is observed.

4. Modulation bandwidth and reliability

The usefull bandwidth of a scanning device is determined by the damping of the system and the onset of the first resonance peak. The resonance frequencies, bandwidths and scan angles are outlined in table 1 for various cantilever beams and in table 2 for various torsional beams. For the cantilever beams a DC voltage 10 % below the threshold value was used whereas a DC voltage 50 % below was used for torsional scanners.

From table 1 and 2 it is found that increasing the modulation bandwidth $\Delta\nu$ results in a reduction in the maximum deflection angle θ_{\max} . Secondly as the mechanical dimensions of the devices is decreased an increase in the threshold levels can be observed.

Table 1 Stepped cantilever beams

l_1	ν_1	$\Delta\nu$	θ_{\max}	V_{th}
μm	kHz	kHz		V
8	363	150	0.2°	46
13	260	110	0.5°	44
18	216	80	0.8°	45
23	163	60	1.0°	41

Table 2 Torsional beams

l_1	ν_1	$\Delta\nu$	θ_{\max}	V_{th}
μm	kHz	kHz		V
C1 5	667	580	2.0°	80
C2 10	410	320	0.9°	49
C5 5	570	480	1.8°	55
C6 10	442	330	1.0°	41

The reliability of the structures were investigated by performing lifetime test on the devices. Six scanner devices were deflected at resonance for more than 10^{11} times without breaking or showing any noticeable deterioration due to fatigue. Comparing with similar endurance test for monocrystalline silicon this suggest that at least for 10^{11} cycles there is no difference in the mechanical stability of the two materials to be observed.⁴

4. Conclusion

A total number of 12 different designs of both torsional and cantilever beam arrays were investigated. With the versatility in design and the compatibility with IC technology this micromachining approach seems very promising.

With respect to the bandwidth and maximum deflection angle the torsional beam scanner geometry seems superior to the cantilever scanner. This is at the expense of a higher DC voltage level required. The endurance test of the devices suggest that aluminum exhibit the same endurance as monocrystalline silicon does at least up to 10^{11} cycles.

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